Heavy hadron spectroscopy at Electron-Ion Colliders

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EIC Semi-inclusive User Group Meeting

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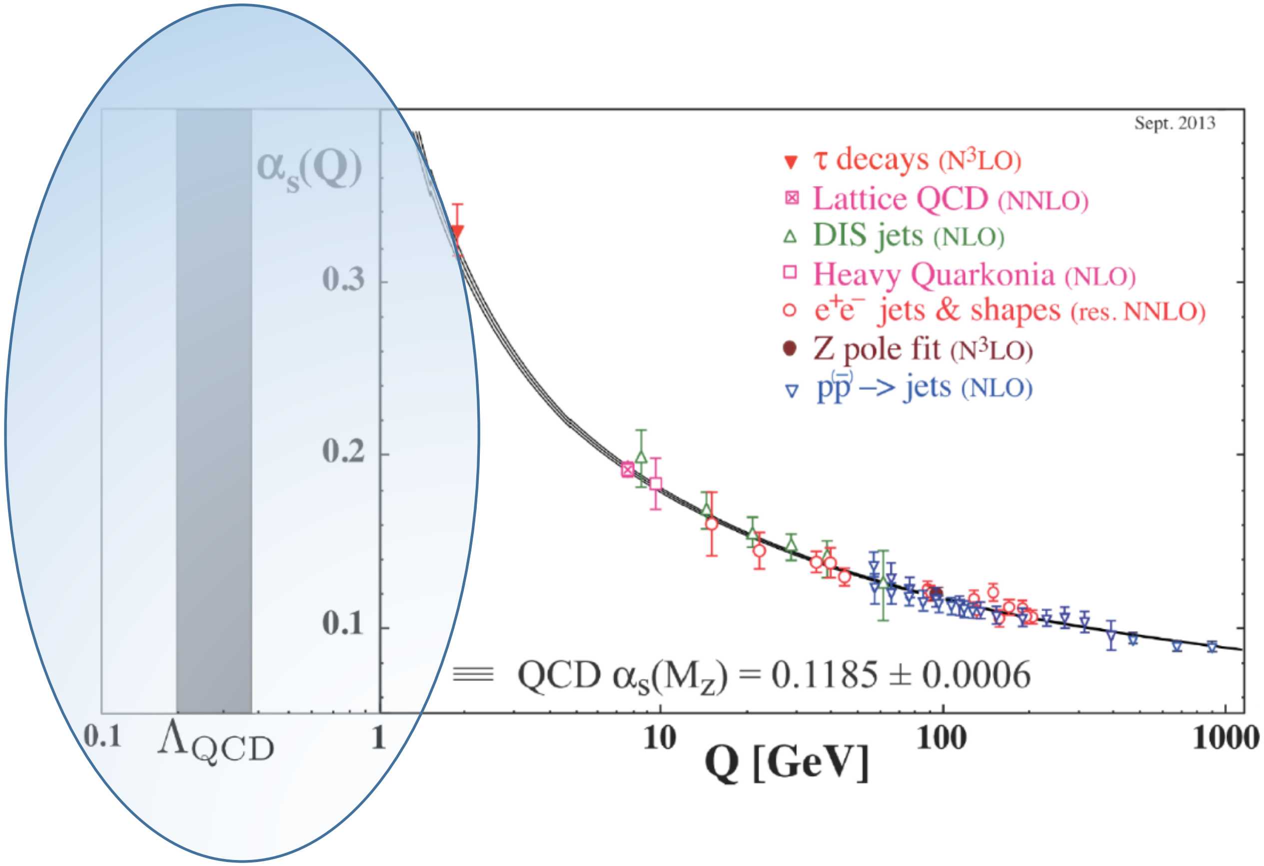
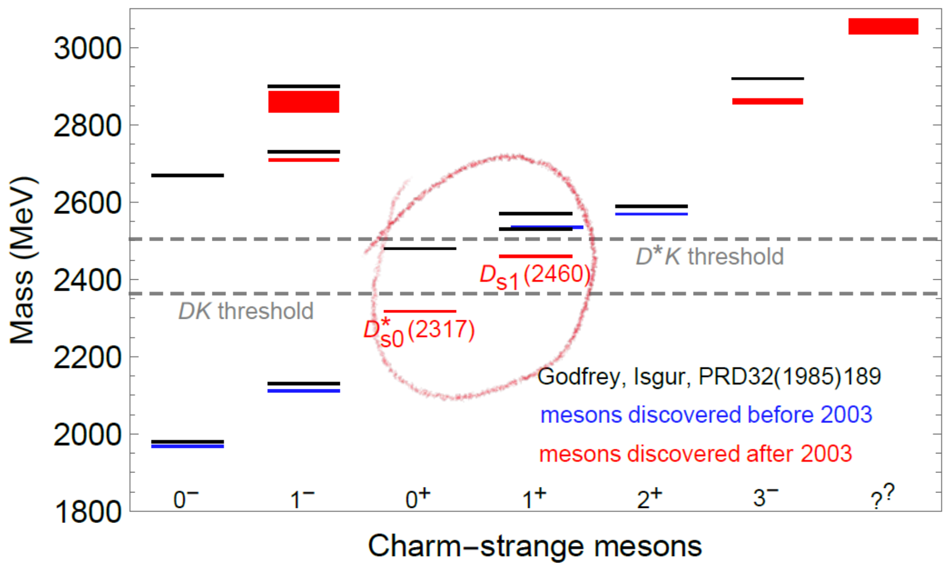
Low-energy QCD: big challenge

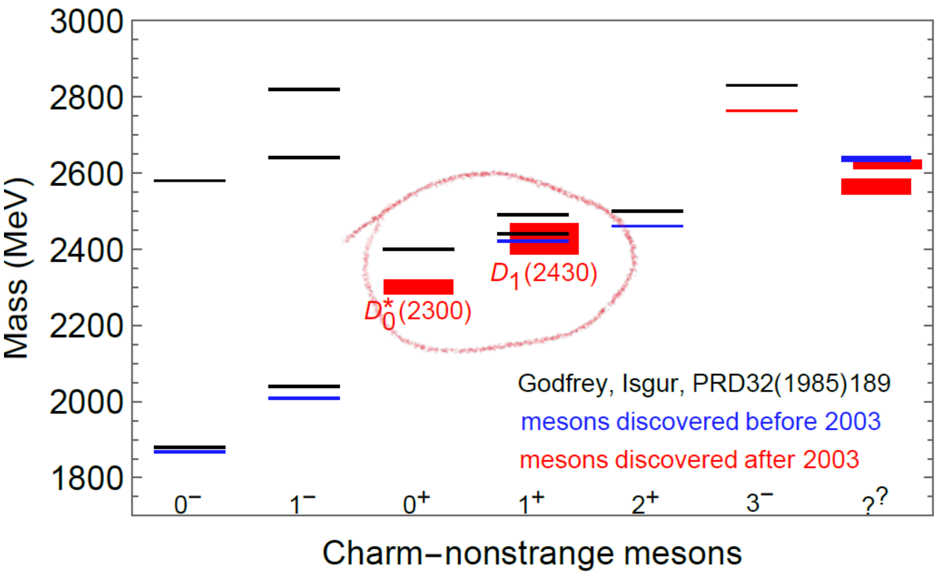


Nucleon structure

Mysteries in hadron spectroscopy

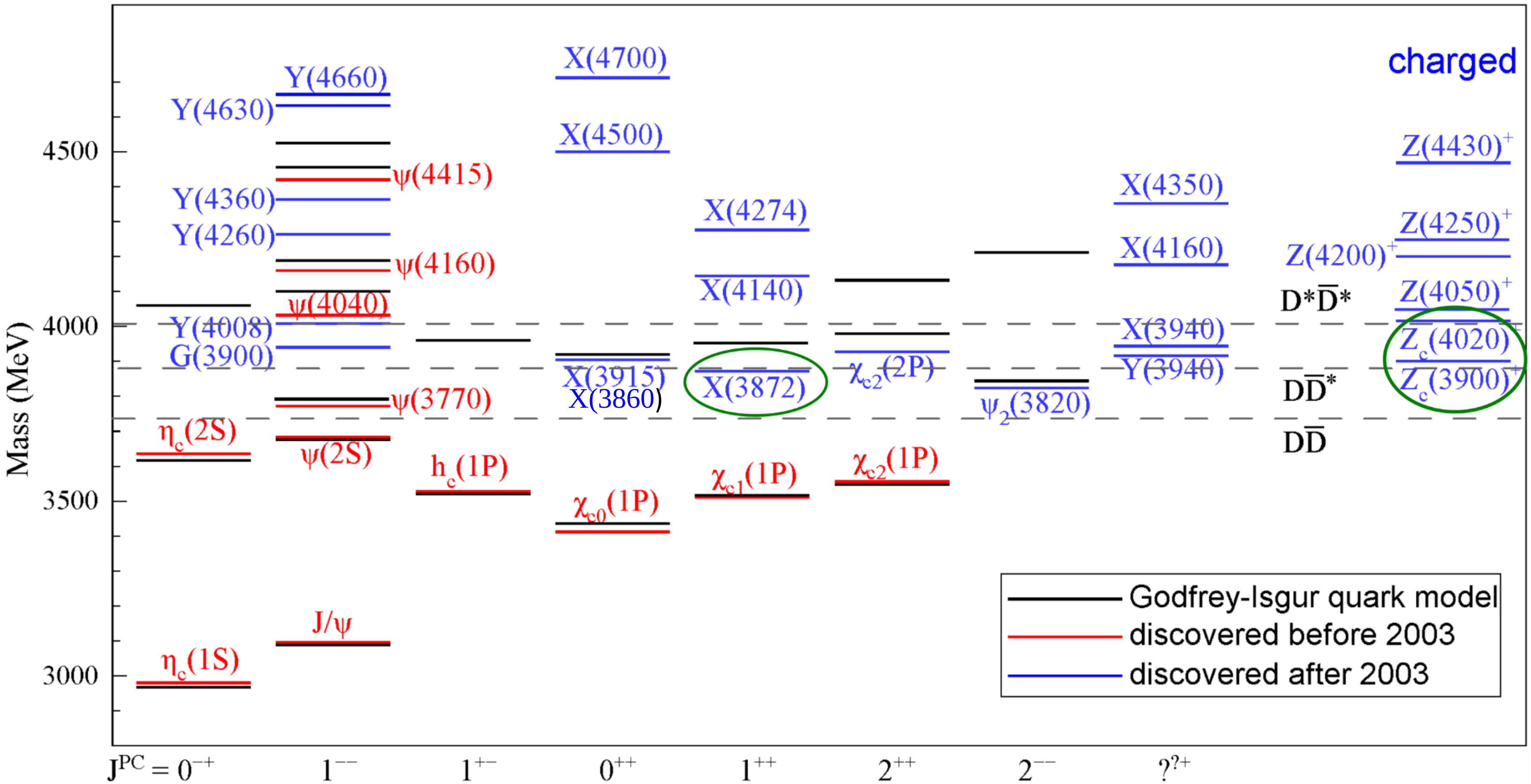
New era of hadron spectroscopy since 2003: Charmed mesons





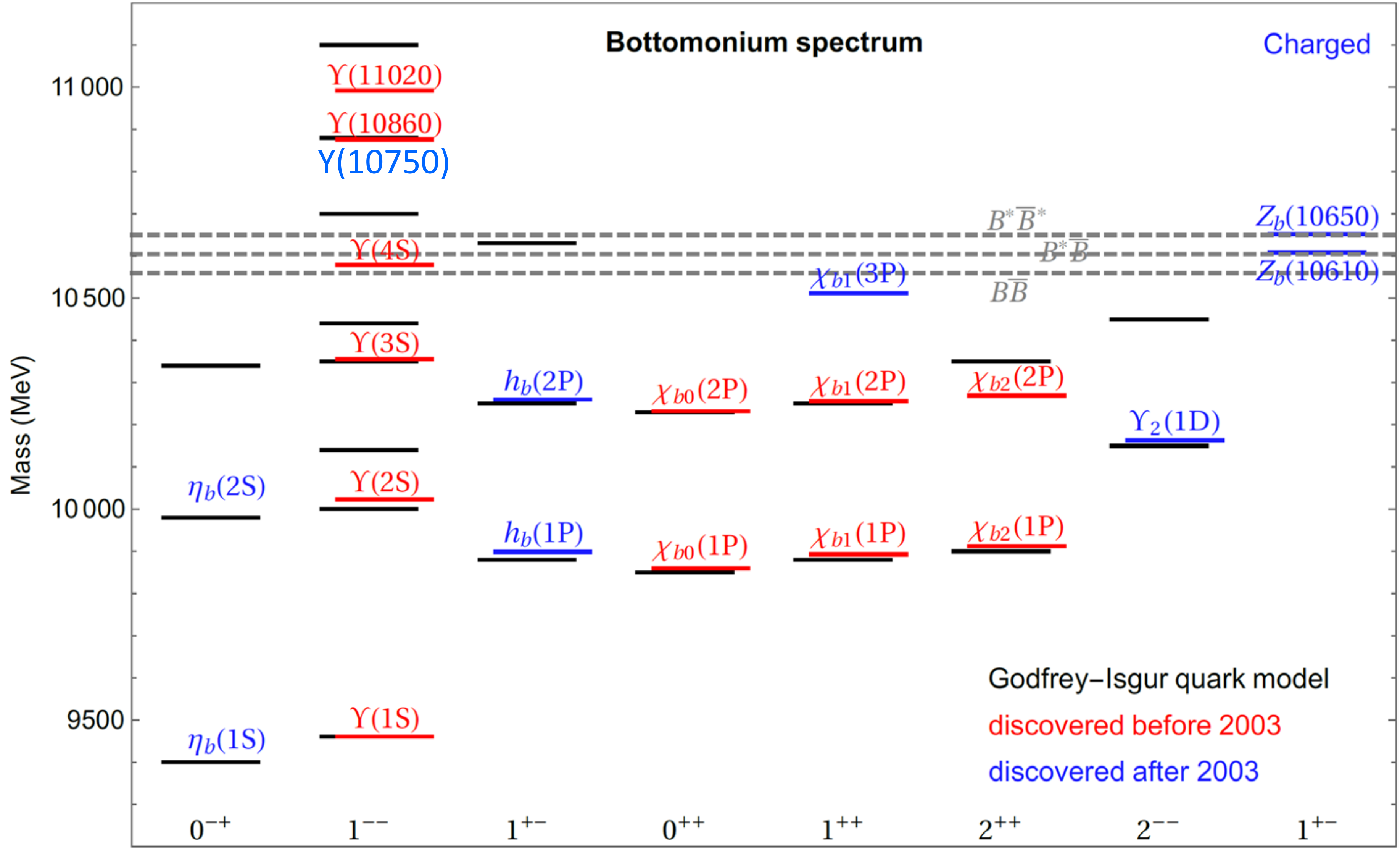
Mass discrepancies

Hidden-charm XYZ states



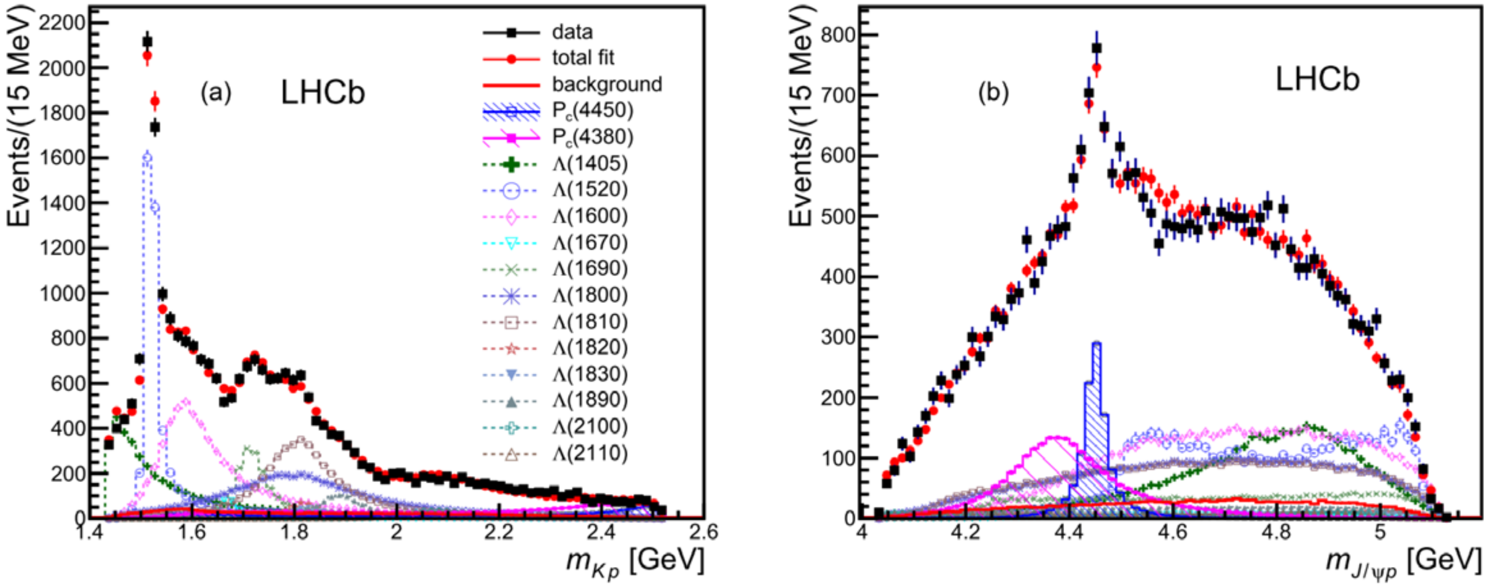
- Some states are very close to two-body S-wave thresholds

Bottomonium spectrum: much less states observed



Pentaquark candidates: P_c

PRL115(2015)072001 [arXiv:1507.03414]



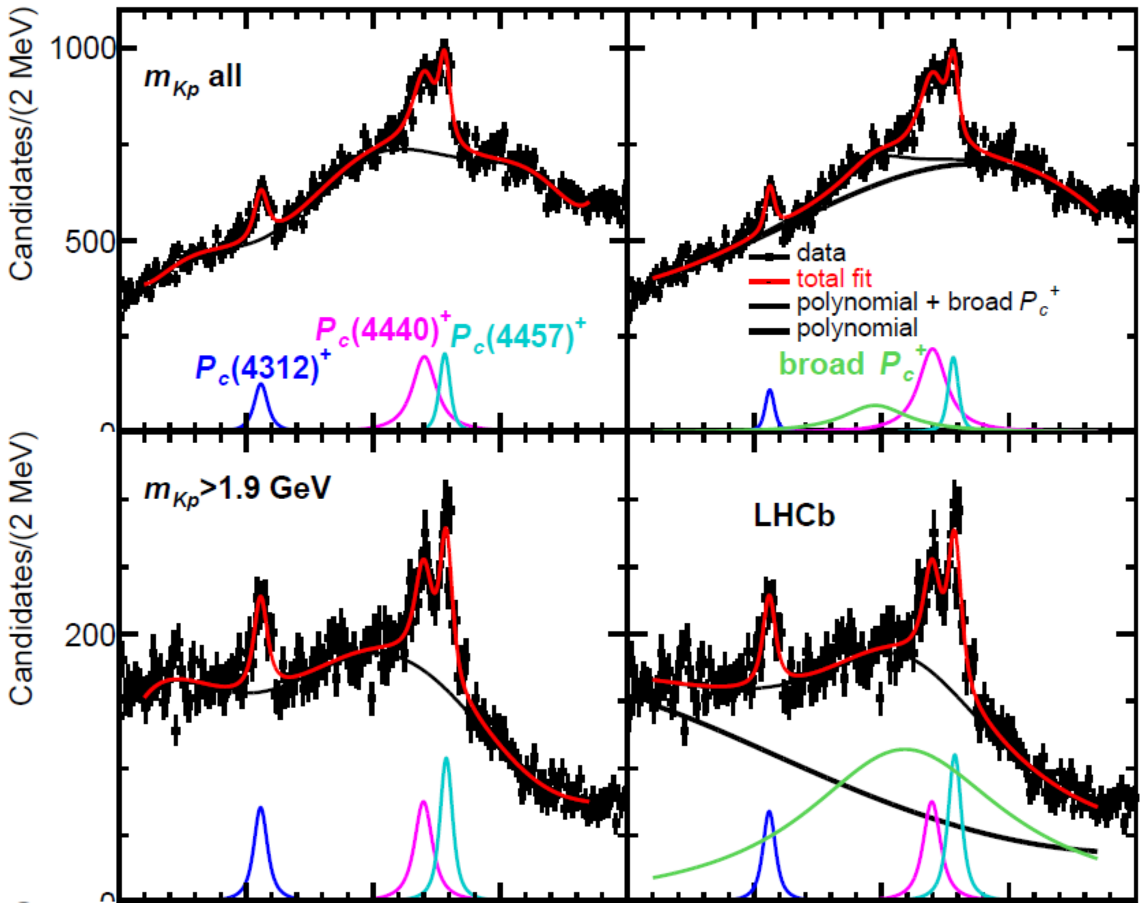
$$M_1 = (4380 \pm 8 \pm 29)\ \text{MeV}, \qquad \Gamma_1 = (205 \pm 18 \pm 86)\ \text{MeV},$$

$$M_2 = (4449.8 \pm 1.7 \pm 2.5)\ \text{MeV}, \qquad \Gamma_2 = (39 \pm 5 \pm 19)\ \text{MeV}.$$

- observed in $J/\psi p$ invariant mass distribution: pentaquark $(c\bar{c}uud)$ candidates

Pentaquark candidates: P_c in 2019

LHCb, PRL122(2019)222001



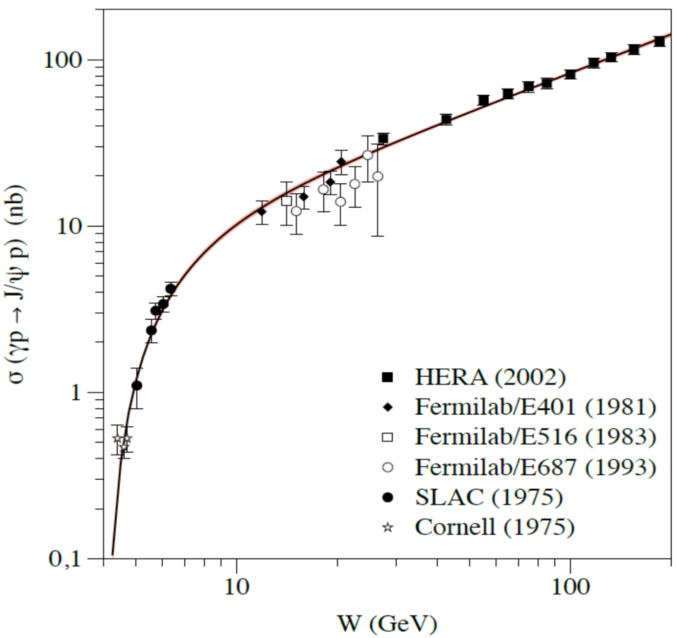
No evidence of Pc at GlueX in $\gamma p \rightarrow J/\psi p$ PRL123(2019)072001

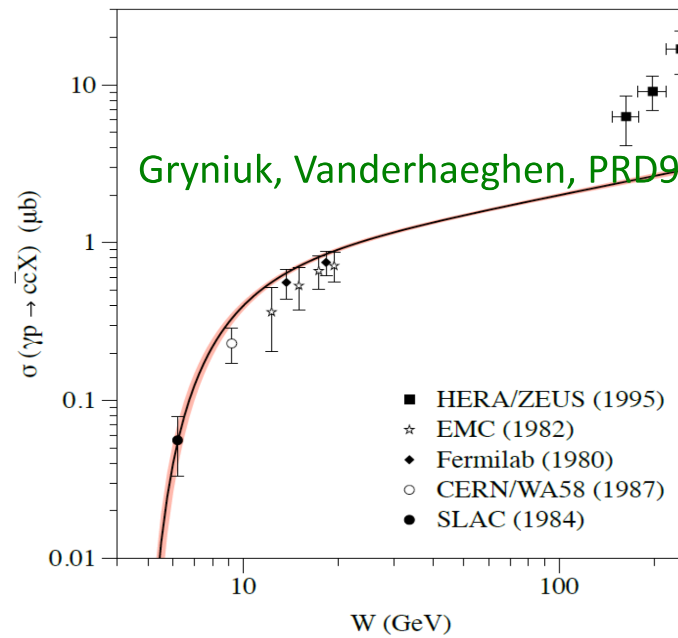
Limits on the branching fraction: $\mathrm{B}(P_c \rightarrow J/\psi p)$ ~ (0.05-0.5)%

X. Cao, J.-P. Dai, PRD100(2019)054033

Production of pentaquarks and XYZ in semi-inclusive processes

- In addition to the final states with J/ψ, it's important to search for hidden-charm XYZ states and pentaquarks through open-charm final states





Gryniuk, Vanderhaeghen, PRD94(2016)074001

- Photoproduction: $\sigma(\gamma p \rightarrow J/\psi p) \sim O(10-100 \text{ nb})$, (no resonant enhancement considered), $\sigma(\gamma p \rightarrow c\bar{c}X) \sim (20-50) \times \sigma(\gamma p \rightarrow J/\psi p)$
- Electroproduction: cross sections are roughly two orders of magnitude (α) smaller
- For an integrated luminosity of 50 fb^{-1}, no. of J/ψ is $\sim O(10^7-10^8)$; many more open-charm hadrons D and Λ_c

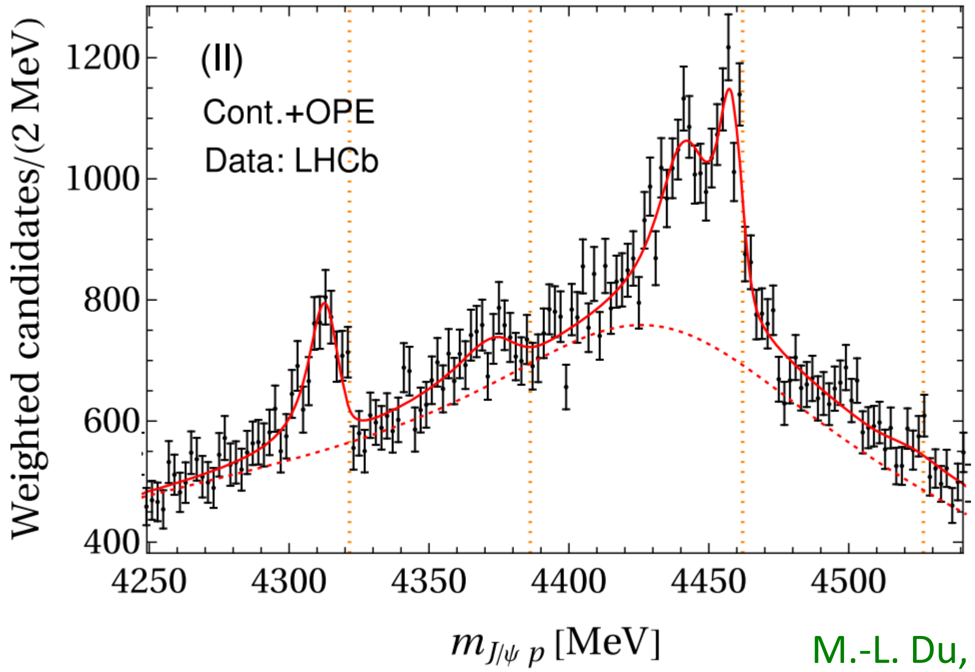
Production of pentaquarks and XYZ in semi-inclusive processes

- $B(P_c \to \Lambda_c \bar{D}^{(*)})$ is expected to be one order of magnitude larger than $B(P_c \to J/\psi p)$

See, e.g., Y.-H. Lin et al., PRD95(2017)114017

- In hadronic molecular model, P_c states couple dominantly to $\Sigma_c^{(*)} \bar{D}^{(*)}$.

J.-J. Wu, B.-S. Zou, E. Oset, J. Nieves, M. Pavon Valderrama, L.-S. Geng, M. Karliner, FKG, …



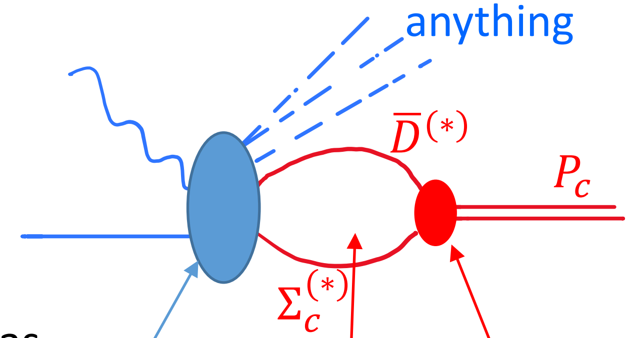
M.-L. Du, V. Baru, FKG, et al., PRL124(2020) 072001

- X(3872) couples dominantly to $D\bar{D}^*$ (>30%); PDG2019

similarly for Zc(3900) BESIII

Production of pentaquarks and XYZ in semi-inclusive processes

- Production of P_c in semi-inclusive reactions:



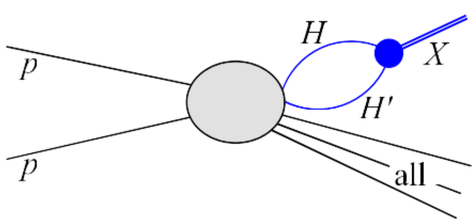
The cross section can be estimated as

$$\propto \underbrace{\sigma\left(\Sigma_c^{(*)}\overline{D}^{(*)}\right)}_{\text{Event generators}} \times |G^{\Lambda}|^2 \times |g_{\text{eff}}|^2$$

Event generators

The method has been used to estimate the X(3872) production at hadron colliders

Artoisenet, Braaten, PRD83(2011)014019; FKG, Meißner, W. Wang, Z. Yang, EPJC74(2014)3063



$\sigma(\text{pp}/\bar{\text{p}}\to\text{X})$ [nb]	Exp.	Λ=0.5 GeV	Λ=1.0 GeV
Tevatron	37-115	7 (5)	29 (20)
LHC-7	13-39	13 (4)	55 (15)

Albaladejo, FKG, Hanhart et al., CPC41(2017)121001

Production of pentaquarks and XYZ in semi-inclusive processes

- There are seven P_c states in hadronic molecular model with heavy quark spin symmetry:

Xiao, Nieves, Oset, 1304.5368; Liu et al., 1903.11560; Sakai et al., 1907.03414; ...

Scheme II	J^P	Pole [MeV]	DC (threshold [MeV])	g_{eff}
$P_c(4312)$	$\frac{1}{2}^-$	$4314(2) - 5(2)i$	$\Sigma_c\bar{D}(4321.6)$	$2.86(12) - 0.44(24)i$
$\mathbf{P_c(4380)}$	$\frac{3}{2}^-$	$4378(2) - 13(3)i$	$\Sigma_c^*\bar{D}$ (4386.2)	$3.00(12) - 0.49(27)i$
$P_c(4440)$	$\frac{3}{2}^-$	$4441(2) - 11(3)i$	$\Sigma_c\bar{D}^*$ (4462.1)	$3.91(11) - 0.62(19)i$
$P_c(4457)$	$\frac{1}{2}^-$	$4459(2) - 4(1)i$	$\Sigma_c\bar{D}^*$ (4462.1)	$2.09(17) - 0.46(18)i$
P_c	$\frac{1}{2}^-$	$4524(2) - 9(1)i$	$\Sigma_c^*\bar{D}^*$ (4526.7)	$1.90(23) - 0.28(21)i$
P_c	$\frac{3}{2}^-$	$4518(2) - 11(2)i$	$\Sigma_c^*\bar{D}^*$ (4526.7)	$2.83(16) - 0.43(18)i$
P_c	$\frac{5}{2}^-$	$4498(5) - 35(17)i$	$\Sigma_c^*\bar{D}^*$ (4526.7)	$4.66(55) - 1.12(32)i$

Production of pentaquarks and XYZ in semi-inclusive processes

- production of the X(3872)

  $\sigma(e^- p \to X(3872) + \text{anything})\, B(X \to J/\psi\pi^+\pi^-)$ at $Q^2 > 1$ GeV^2 estimated using NRQCD with input from hadron colliders (courtesy of Xiaojun Yao)

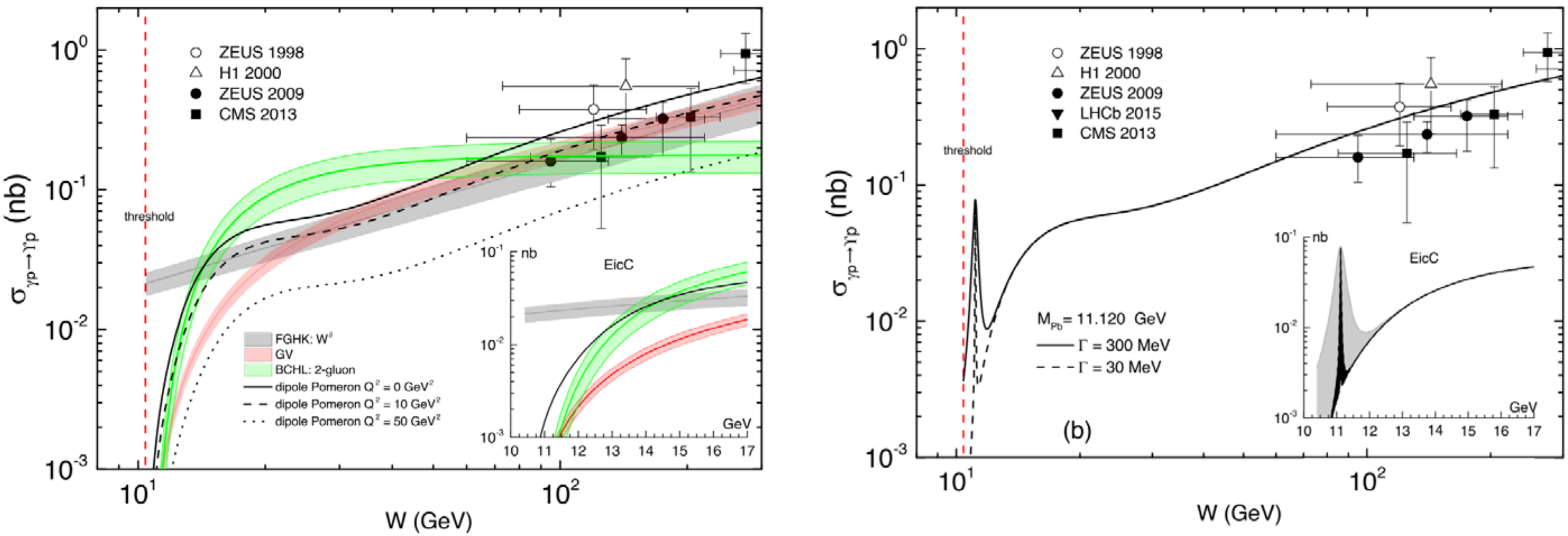
CM energy	10 GeV	15 GeV	20 GeV	100 GeV
Cross section	0.04 pb	0.13 pb	0.26 pb	2.6 pb

Considering an integrated luminosity of 50 fb^{-1}, no. of $X(3872)$ is $\sim O(10^3 - 10^5)$

Exclusive production of P_b

- P_b states (bottom analogue of P_c)

X. Cao, FKG, Y.T. Liang et al., 1912.12054



Nonresonant: fitted using the soft dipole Pomeron model

Martynov, Predazzi, Prokudin, EPJC26(2002)271, PRD67(2003)074023

Assuming $\mathrm{B}(P_b \to \Upsilon p) = 5\%$ ($(0.5-5)\%$ for the band inserted plot)

- Photoproduction: $\sigma(\gamma p \to \Upsilon p) \sim O(10^{-2}\text{-}10^{-1}\mathrm{nb})$, $\sigma(\gamma p \to b\bar{b}X)$ is about two orders higher; possibility of detecting the open-bottom hadrons B and Λ_b?

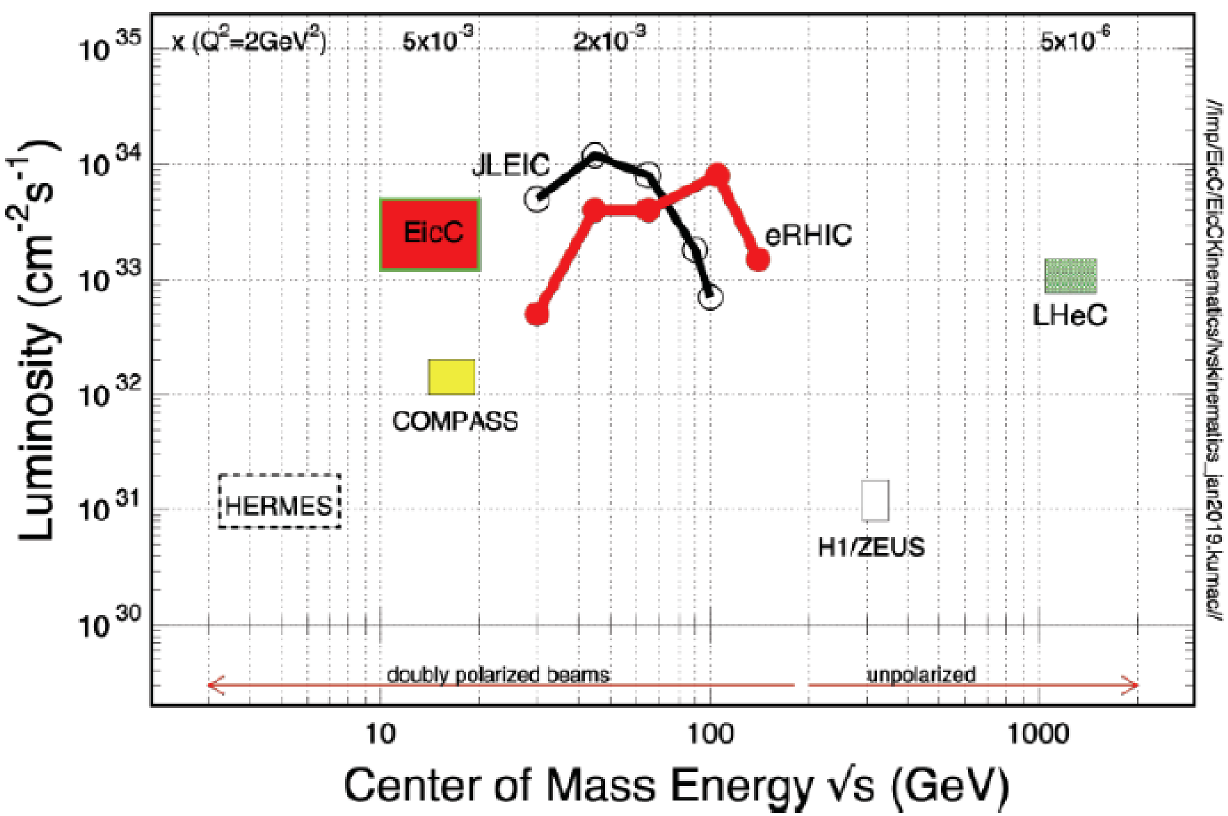
Summary

- EIC and EicC will also contribute a lot to hadron spectroscopy
- Consider open-flavor final states (challenge: detection efficiency?)
- Supplementary to existing experiments Different production mechanisms: free of triangle singularities in B and Λ_b decays

Complementary to

Thank you for your attention!

EicC: Electron-ion collider in China

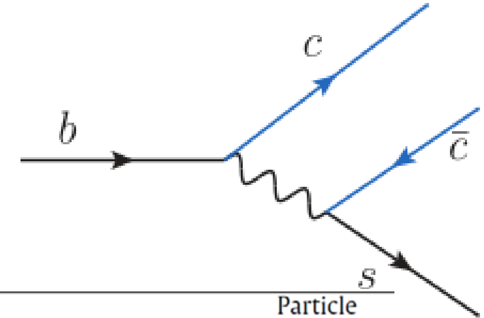


- CM energy: 15-20 GeV
- Luminosity: (2-4) * 10^{33} $cm^{-2}s^{-1}$
- Polarized beams

Production processes of hidden-charm states

XYZ	产生过程	衰变道
$X(3872)$	$B \to KX/K\pi X, e^+e^- \to \gamma X,$ $pp/p\bar{p}$ 单举	$\pi^+\pi^- J/\psi, \omega J/\psi, D^{*0}\bar{D}^0, \gamma J/\psi, \gamma\psi(2S)$
$X(3915)$	$B \to KX, \gamma\gamma \to X$	$\omega J/\psi$
$X(4140)$	$B \to KX, p\bar{p}$ 单举	$\phi J/\psi$
$X(4274)$	$B \to KX$	$\phi J/\psi$
$X(4500)$	$B \to KX$	$\phi J/\psi$
$X(4700)$	$B \to KX$	$\phi J/\psi$
$X(3940)$	$e^+e^- \to J/\psi + X$	$D\bar{D}^*$
$X(4160)$	$e^+e^- \to J/\psi + X$	$D^*\bar{D}^*$
$X(4350)$	$\gamma\gamma \to X$	$\phi J/\psi$
$Y(4008)$	$e^+e^- \to Y$	$\pi\pi J/\psi$
$Y(4260)$	$e^+e^- \to Y$	$\pi\pi J/\psi, D\bar{D}^*\pi, \chi_{c0}\omega, h_c\pi\pi$
$Y(4360)$	$e^+e^- \to Y$	$\pi\pi\psi(2S)$
$Y(4660)$	$e^+e^- \to Y$	$\pi\pi\psi(2S), \Lambda_c\bar{\Lambda}_c$
$Z_c(3900)$	$e^+e^- \to \pi Z_c$, b 强子单举衰变	$\pi J/\psi, D\bar{D}^*$
$Z_c(4020)$	$e^+e^- \to \pi Z_c$	$\pi h_c, D^*\bar{D}^*$
$Z_1(4050)$	$B \to KZ_c$	$\pi^\pm \chi_{c1}$
$Z_2(4250)$	$B \to KZ_c$	$\pi^\pm \chi_{c1}$
$Z_c(4200)$	$B \to KZ_c$	$\pi^\pm J/\psi$
$Z_c(4430)$	$B \to KZ_c$	$\pi^\pm J/\psi, \pi^\pm\psi(2S)$

Production processes of hidden-charm states



- In weak decays $b \to [c\bar{c}]s$

Three/four-body hadronic decays: $B \to K\, X$, $\Lambda_b \to K\, P_c$

Process	Production	Decay	Particle
B and Λ_b decays	$B \to K + X$	$X \to \pi^+\pi^- J/\psi$ [4,110–115] $X \to D^{*0}\bar{D}^0$ [116–118] $X \to \gamma J/\psi$ [119–122] $X \to \gamma\psi(2S)$ [119,121]	$X(3872)$
		$X \to \omega J/\psi$ [107,123,124]	$X(3872)$ $Y(3940)$
		$X \to \gamma\chi_{c1}$ [125]	$X(3823)$
		$X \to \phi J/\psi$ [126–133]	$Y(4140)$ $Y(4274)$ $X(4500)$ $X(4700)$
	$B \to K + Z$	$Z \to \pi^\pm\chi_{c1}$ [134,135]	$Z_1(4050)$ $Z_2(4250)$
		$Z \to \pi^\pm J/\psi$ [46,136]	$Z_c(4200)$ $Z_c(4430)$
		$Z \to \pi^\pm\psi(2S)$ [30,136–140]	$Z_c(4240)$ $Z_c(4430)$
	$B \to K\pi + X$	$X \to \pi^+\pi^- J/\psi$ [141]	$X(3872)$
	$\Lambda_b \to K + P_c$	$P_c \to pJ/\psi$ [35]	$P_c(4380)$ $P_c(4450)$

Lebed, Mitchell, Swanson, PPNP93(2017)143

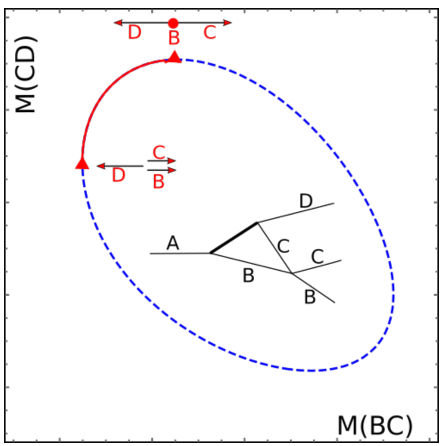
- Masses limited to

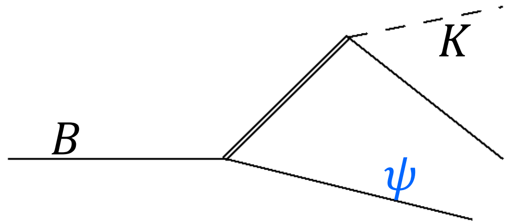
$$M_B - M_K \approx 4.8\ \text{GeV} \qquad M_{\Lambda_b} - M_K \approx 5.1\ \text{GeV}$$

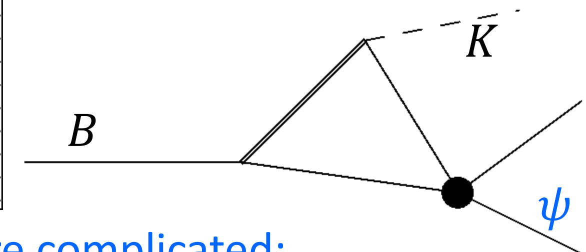
- Masses of initial states fixed

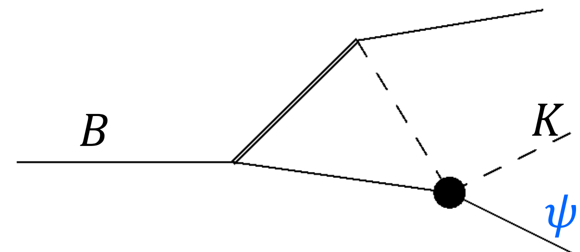
Production processes of hidden-charm states

- Difficulties for multi-hadron final states
  - ✓ Many resonances from the cross channel:
    branching fractions often unknown, interference between overlapping resonances, multi-channel unitarity, …





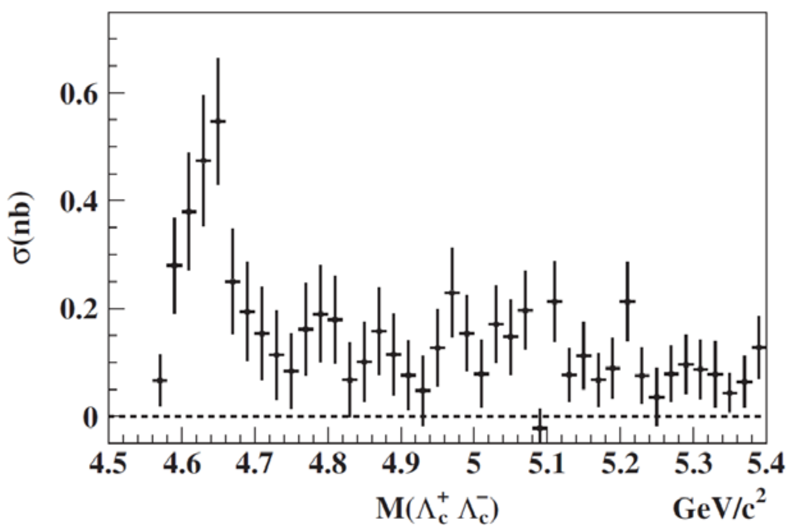




  - ✓ 3-body FSI is even more complicated:
    intermediate states can be different from external ones; threshold cusps; triangle singularities or more complicated Landau singularities
  - ✓ We need combined th.+exp. efforts: other production processes; better knowledge of light-flavor resonances; amplitude analysis framework considering the above subtleties

Production processes of hidden-charm states

- In e^+e^- collisions,
  - Energy coverage limited: $\lesssim 4.6$ GeV @BESIII, thus
    - ✓ Vector heavy quarkonia; little is known above that energy (BESIII is taking data);
    - ✓ for other quantum numbers, even lower mass accessible: $e^+e^- \to X + \gamma/\mathrm{pions}$; resonances decaying into $\psi\phi$, $\psi\omega$ cannot be studied
    - ✓ No access to charm-anticharm baryon-pair thresholds, e.g., $\Lambda_c^+\Lambda_c^-$; no access to thresholds of a pair of excited charm mesons, e.g., $D_1\bar{D}_1$



$e^+e^- \to \gamma_{\mathrm{ISR}}\Lambda_c^+\Lambda_c^-$

Belle, PRL101(2008)172001

  - $e^+e^- \to \gamma_{\mathrm{ISR}} Y$ and two-photon processes: much lower rates